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Role of intensive intersubband transitions in Shubnikov–de Haas oscillations and in weak localization

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Abstract. Shubnikov–de Haas conductivity oscillations are calculated taking into account intensive intersubband transitions between levels of size quantization in a quantum well and compared with anomalous magnetoresistance under weak localization conditions.

Introduction

The most widely used nanostructures characterization method is investigation of their properties in magnetic field. The Shubnikov–de Haas effect and the anomalous magnetoresistance measurements in weak field are often applied.

In the ultra-quantum case of one size-quantized subband filling these phenomena are investigated very well both theoretically and experimentally. At two and more subbands occupation the new peculiarities appear in these effects caused by intersubband transitions. For instance, if the scattering cross-section is anisotropic then conductivity of the 2D electron gas is not reduced to the sum of conductivities in each subband. Therefore one has to take into account intersubband transitions in the weak localization theory, Shubnikov–de Haas effect and quantum Hall effect to determine exactly such parameters as carrier concentration, diffusion coefficient and spin relaxation times.

In this report the role of intersubband transitions is demonstrated in anomalous magnetoresistance effect and Shubnikov–de Haas oscillations.

1 Weak localization

It has been shown [1] that in the case of intensive intersubband transitions the anomalous conductivity in weak magnetic field B is described by the standard expression:

$$\sigma(B) - \sigma(0) = \frac{e^2}{4\pi^2\hbar} \left[2 f_2 \left(\frac{B}{B_\varphi + B_\parallel} \right) + f_2 \left(\frac{B}{B_\varphi + B_\perp} \right) - f_2 \left(\frac{B}{B_\varphi} \right) \right], \quad (1)$$

where

$$B_\varphi = \frac{\hbar c}{4eD\tau_\varphi}, \quad B_{\parallel,\perp} = \frac{\hbar c}{4eD\tau_{\parallel,\perp}}, \quad (2)$$

the function f_2 is given by: $f_2(x) = \ln x + \psi(1/2 + 1/x)$, and $\psi(y)$ is a Digamma-function. Here τ_φ is a phase relaxation time and $\tau_{\parallel,\perp}$ are the longitudinal and transverse spin relaxation times where the role of the indicated axis plays the normal to the QW plane. D is an averaged diffusion coefficient, determining the whole conductivity of the system. It is important to note that this average is not reduced to the half-sum of the diffusion coefficients in each subband. The relaxation rates τ_φ , τ_\parallel and τ_\perp are also quantities averaged over subbands.

Thus the intensive intersubband transitions change essentially the dependence of conductivity on magnetic field. Instead of two contributions like Eq. (1) from each subband with six characteristic magnetic fields one has three parameters averaged over two subbands.

2 Shubnikov–de Haas effect

Since periods of Shubnikov–de Haas oscillations are determined by crossing of Landau levels in each subband by the Fermi level the intersubband transitions do not change the functional dependence of conductivity on the magnetic field. However the contributions of each size-quantized subband depend both on the transitions intensity and on the angle dependence of scattering cross-section. In this report the case of isotropic scattering is considered for simplicity.

The expression for the dissipative conductivity has a view:

$$\sigma_{xx} = \frac{n_1 e^2 \tau_1 / m}{1 + (\omega_c \tau_1)^2} \left\{ 1 - 2 \frac{(\omega_c \tau_1)^2}{1 + (\omega_c \tau_1)^2} \left[\left(1 - \frac{\tau_1}{\tau_{12}} \right) \delta_1 + \frac{\tau_1}{\tau_{12}} \delta_2 \right] - \frac{\tau_1}{\tau_{12}} (\delta_1 - \delta_2) \right\} \\ + \frac{n_2 e^2 \tau_2 / m}{1 + (\omega_c \tau_2)^2} \left\{ 1 - 2 \frac{(\omega_c \tau_2)^2}{1 + (\omega_c \tau_2)^2} \left[\left(1 - \frac{\tau_2}{\tau_{12}} \right) \delta_2 + \frac{\tau_2}{\tau_{12}} \delta_1 \right] - \frac{\tau_2}{\tau_{12}} (\delta_2 - \delta_1) \right\}, \quad (3)$$

where m is the electron effective mass, ω_c is its cyclotron frequency, $n_{1,2}$ and $\tau_{1,2}$ are respectively concentration and momentum relaxation time in the first and second subbands, and τ_{12} is the intersubband transition time. The oscillating parts are given by:

$$\delta_1 = 2 \cos \left(2\pi \frac{E_F}{\hbar \omega_c} \right) \exp \left(-\frac{\pi}{\omega_c \tau_1} \right), \quad \delta_2 = 2 \cos \left(2\pi \frac{E_F - \Delta}{\hbar \omega_c} \right) \exp \left(-\frac{\pi}{\omega_c \tau_2} \right), \quad (4)$$

where E_F and $E_F - \Delta$ are Fermi levels reckoned from bottoms of the first and second subbands of size quantization. Here Δ is the energy distance between subbands.

The peculiarity of Eq. (3) is that the main signal with the frequency $2\pi E_F / \hbar$ is modulated by the slow changing oscillation even at low occupation of the excited subband: $E_F - \Delta \sim n_2 \ll n_1$.

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References

- [1] N.S. Averkiev, L.E. Golub and G.E. Pikus, *Solid State Commun.* **107**, 757 (1998); *Semiconductors* **32**, 1087 (1998).